APPLICATION FOR UNITED STATES LETTERS PATENT

for

INLINE PHASE SHIFTER

by

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Attorney Docket No. 017750-698

INLINE PHASE SHIFTER

BACKGROUND

Field of the Invention

[0001] The present invention relates to a phase shifter, and in particular, to an inline phase shifter.

Background Information

[0002] A first type of phase shifter is an electrically reactive structure in which electrical reactive properties are altered by applied voltages or by changing the relation between electrically reactive elements. US Patent No. 5,309,166 to Collier et al., hereby incorporated by reference, discloses a phase shifter in which electrical reactive properties are altered by applied voltages. US Patent No. 5,504,466 to Chan-Son-Lint et al., hereby incorporated by reference, discloses a phase shifter in which electrical reactive properties are altered by changing the relation between electrically reactive elements with a piezoelectric element.

[0003] A second type of phase shifter is a delay type phase shifter that uses a switch to switch between signal paths in combination with electrical reactive elements. US Patent No. 6,184,827 to Dendy et al., hereby incorporated by reference, discloses a phase shifter in which the signal path is altered by changing the length of the signal path with a MEMS

switch to switch between lengths of transmission line.

[0004] The first and the second types of devices can phase shift a signal within a range of phases but inherently degrade the signal strength because of power losses due to electrical resistances.

[0005] A third type of phase shifter is a fixed waveguide having fixed dimensions in terms of the cross-sectional area of the waveguide path through the waveguide and the length of the waveguide. The fixed waveguide can phase shift a signal with minimal signal strength degradation. However, a fixed waveguide can only phase shift a signal to one predetermined phase based on the physical dimensions of the waveguide.

SUMMARY OF THE INVENTION

[0006] The present invention is directed to an inline phase shifter. Exemplary embodiments of the invention dynamically change the physical dimensions of a waveguide path with an electromechanical means to phase shift a signal to any phase within a range of phases. A signal can be phase shifted to a predetermined degree of phase shift within a range of phases by controlling the physical dimensions of the waveguide path.

[0007] Exemplary embodiments of the present invention include a waveguide having a waveguide path within the waveguide and at least one electromechanical means for changing a physical dimension of the waveguide path to phase shift a signal that travels along the waveguide path. The exemplary embodiments also include a method for phase shifting a signal that includes changing physical dimensions of a waveguide path by actuating an electro-mechanical device and inputting a signal along the waveguide path to output a phase shifted signal. Exemplary embodiments are also directed to an inline phase

shifter that includes a waveguide having a waveguide path and a first plurality of electromechanical devices positioned serially along the waveguide path sufficiently adjacent to the waveguide path to change a physical dimension of the waveguide path upon actuation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The accompanying drawings, which are included to provide a further understanding of the invention and are incorporated in and constitute a part of this specification, illustrate embodiments of the invention that together with the description serve to explain the principles of the invention. In the drawings:

[0009] Fig. 1 is a perspective view of an exemplary embodiment using electromechanical devices.

[0010] Fig. 2 is a cross-sectional view along line A-A' of the first exemplary embodiment of Fig. 1.

[0011] Fig. 3 is a cross-sectional view along line B-B' of an exemplary means in the first exemplary embodiment of Fig. 1.

[0012] Fig. 4 is a perspective representation of a change of the physical dimensions of a waveguide path according to an exemplary embodiment of the present invention, and an electrical model thereof.

[0013] Fig. 5 is a perspective view of an exemplary embodiment using micro-mechanical devices.

[0014] Fig. 6 is a perspective view of a first row and a second row of exemplary

electromechanical means of Fig. 5.

[0015] Fig. 7 is an exemplary radar system configured in accordance with the present invention.

[0016] Fig. 8 is an exemplary method of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0017] Fig. 1 is an exemplary embodiment of a waveguide having a waveguide path within a waveguide, and an electromechanical means for changing a physical dimension of the waveguide path to phase shift a signal that travels along the waveguide path. In the exemplary embodiment of Fig. 1, a dynamic inline phase shifter 100 includes a waveguide 102 through which a signal can travel along a waveguide path 104. The waveguide 102 has a first (e.g., top) surface 102a and a second (e.g., bottom) surface 102b that are parallel to one another. Positioned adjacent to and along the top surface 102a are a first electromechanical means 106, a second electromechanical means 108, and a third electromechanical means 110. Positioned adjacent to and along the bottom surface 102b are a fourth electromechanical means 112, a fifth electromechanical means 114, and a sixth electromechanical means 116.

[0018] The first electromechanical means 106, second electromechanical means 108, and a third electromechanical means 110 can be a plurality of electromechanical devices positioned serially along the waveguide path sufficiently adjacent to the waveguide path to change a physical dimension of the waveguide path upon actuation of at least one of the plurality of electromechanical devices. As referenced herein, an electromechanical device is positioned sufficiently adjacent to the waveguide path when it can alter a physical

dimension of the waveguide path by any detectable amount. In addition, the fourth electromechanical means 112, fifth electromechanical means 114, and sixth electromechanical means 116 can be another plurality of electromechanical means positioned serially along the waveguide path sufficiently adjacent to the waveguide path to change a physical dimension of the waveguide path upon actuation of at least one of the other plurality of electromechanical devices. Each of the electromechanical means 106-116 is one of a piezoelectric device, micro-electromechanical device, electrostatic device, or another type of electromechanical device suitable for changing a physical dimension of the waveguide path.

[0019] As shown in the exemplary Fig. 1 embodiment, a plane containing the first electromechanical means 106 and fourth electromechanical means 112 is normal to the waveguide path 104 at point 118 and the planes containing the other sets of electromechanical means 108/114 and 110/116 are normal to the waveguide path 104 at points 120 and 122, respectively. As referenced herein, "normal" refers to being oriented relative to the path in a manner sufficient to impact the path upon actuation. Each of the electromechanical means 106-116 respectively has a shutter 124-134. The upper shutters 124-128 can descend toward the bottom surface 102b and the lower shutters 130-134 can ascend toward the top surface 102a. Between each of the shutters (e.g., 124 and 130) of a respective set of electromechanical means (e.g., 106 and 112) there is an opening (e.g., 136) normal to the waveguide path 104 between the shutters (e.g., 124 and 130). The height of the opening (e.g., 136) between respective shutters (e.g., 124 and 130) is

dependent upon the amount of actuation that has taken place in their respective electromechanical means (e.g., 106 and 112).

[0020] As shown in Fig. 2, which is a cross-sectional view 200 along line A-A' of the exemplary embodiment 100 in Fig.1, side surfaces of the upper shutters 224-228 can be electrically connected (directly or indirectly) to the top surface 202a of the waveguide 202 with conductive means, such as spring fingers 242-252 or any other suitable conductor or semiconductor. Side surfaces of the lower shutters 230-234 are electrically connected (directly or indirectly) to the bottom surface 202b of the waveguide 202~~a~~ with a set of spring fingers 254-264. In the alternative, or in addition, electrical connection can be made with, for example, conductive brush like structures. Flexible conductive films can also be attached at points along the sides of the shutters with enough slack in the film to allow the shutters to move up and down.

[0021] As shown in Fig. 3, which is a cross-sectional view along line B-B' of an exemplary means 110 in Fig.1, the electromechanical means is a piezoelectric device 310 having a shutter 326 that is connected to the central point 366 of a piezoelectric element 368. The ends of the piezoelectric element 368 are attached to the housing 311 of the piezoelectric device 310. The representation of the shutter 326, the central point 366 and the piezoelectric element 368 in solid lines of Fig. 3 is an illustration of an actuated state of the device (e.g., a voltage is being applied across the piezoelectric element 368 by wires at the ends of the piezoelectric element 324). The representation of the shutter 326', the central point 366' and the piezoelectric element 368' in dashed lines is an illustration of an unactuated state of the device (e.g., no voltage is being applied across the piezoelectric

element 368'). The magnitude of the voltage applied to the piezoelectric element can be used to determine the amount of movement or actuation that the shutter 326 will undergo, and the final position 370 that the shutter will hold. The shutter 326 can move to, and hold, any position within a range of positions 372 depending upon the voltage applied across the piezoelectric element 324.

[0022] Fig. 4 is an exemplary representation 400 of a change of the physical dimensions of the waveguide 402 along the waveguide path 404 resulting from an implementation of the embodiment shown in Fig. 1 and a transmission line model of the implementation. A first voltage is applied to the first electromechanical means 124, the third electromechanical means 128, the fourth electromechanical means 130, and the sixth electromechanical means 134 of Fig. 1 that actuates the respective shutters of these means to a first position. The actuated positions for the shutters of the first, third, fourth, and sixth electromechanical means are respectively shown in Fig. 4 as a first shutter structure 424, a third shutter structure 428, a fourth shutter structure 430, and a sixth shutter structure 434. A second voltage is applied to the second electromechanical means 126 and fifth electromechanical means 132 of Fig. 1 that actuates the respective shutters of theses means to a second position different than the first position of the shutters in the first, third, fourth, and sixth electromechanical means. The actuated positions for the shutters of the second and fifth electromechanical means are respectively shown as a second shutter structure 426 and a fifth shutter structure 432 in Fig. 4.

[0023] The actuation of the shutters 424-434 into the waveguide 402 changes the physical

dimensions of the waveguide path 404, as shown in Fig. 4. For example, the cross-sectional area of the waveguide path 404 at a point B in the opening Ob between the first shutter structure 424 and fourth shutter structure 430 has been reduced. Further along the waveguide path 404 at a point C in the opening Oc between the second shutter structure 426 and the fifth shutter structure 432 the cross-sectional area is further reduced. At point D along the waveguide path 404, the cross-sectional area in the opening Od between the third shutter structure 428 and fourth shutter structure 434 is the same as the cross-sectional area between the first shutter structure 424 and fourth shutter structure 430.

[0024] The multiple-stub technique (i.e., multiple sets of shutters) works for any number of stubs (i.e., sets of shutters). A single stub can provide phase shift, but reflect some the wave. Using two or more stubs, through proper choice of stub lengths (i.e., actuation of sets of shutters) and separations (i.e., distance between sets of shutters), reflections from each of the stubs can cancel so that a reduced overall reflection is seen at both ports of the waveguide 402.

[0025] As shown in Fig. 4, the admittance Y along the waveguide path 404 can be modeled to use impedance matching techniques of transmission line theory. Each opening Ob, Oc, and Od represents a stub in the transmission line equivalent model. The admittance Y of each stub (i.e., set of shutters) is a function of the cross-sectional area of an opening, and the separations L (i.e., Lbc and Lcd) between openings (i.e., Ob, Oc, and Od) affect how the reflections from these admittances combine to yield the overall reflection seen at both ports of the waveguide 402. Since the separations are fixed, the combination of openings is chosen via actuation of shutters so that the desired amount of phase shift and

impedance match is achieved. For example, in Fig. 4, the combined reflection from the two outboard stubs nominally cancels the reflection from the center stub. Symmetry of the stub arrangement reduces losses due to reflection but is not necessary.

[0026] Fig. 5 illustrates an exemplary embodiment 500 of a dynamic inline phase shifter having a waveguide 502 through which a signal travels in one of two directions (e.g. bi-directional) along the waveguide path 504. The waveguide 502 has a first (e.g., top) surface 502a and a second (e.g., bottom) surface 502b that are parallel to each other. Positioned within the waveguide 502 adjacent to and along the top surface are a first electromechanical means 506, a second electromechanical means 508, and a third electromechanical means 510. Positioned within the waveguide 502 adjacent to and along the bottom surface 502b are a fourth electromechanical means 512, a fifth electromechanical means 514, and a sixth electromechanical means 516. The first electromechanical means
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406, second electromechanical means 508 and third electromechanical means 510 are a plurality of electromechanical means positioned serially along the waveguide path 504 sufficiently adjacent to the waveguide path 504 to change a physical dimension of the waveguide path upon actuation of at least one of the electromechanical means. In addition, the fourth electromechanical means 512, fifth electromechanical means 514, and sixth electromechanical means 516 are another plurality of electromechanical means positioned serially along the waveguide path 504 sufficiently adjacent to the waveguide path 504 to change a physical dimension of the waveguide path upon actuation of at least one of the electromechanical means. Each of the electromechanical means 506-516 is an array of

piezoelectric devices, an array of micro-electromechanical devices, or an array of other types of electromechanical devices suitable for changing a physical dimension of the waveguide path.

[0027] As shown in Fig. 5, each of the arrays 506-516 has first and second rows of micro-electromechanical devices, respectively shown as x and y in Fig. 5. Each of the micro-electromechanical devices in rows x and y of arrays 506-510 has a shutter 524. Each of the micro-electromechanical devices in rows x and y of arrays 512-516 has a shutter 526. The shutters 524 of arrays 506-510 can move or unroll toward the bottom surface 502b and the shutters 526 of arrays 512-516 can move or unroll toward the top surface 502a. Each of the micro-electromechanical devices in row x of arrays 506-510 is connected (directly or indirectly) to the top surface 502a of the waveguide with a conductive strip 530. Each of the micro-electromechanical devices in row x of arrays 512-516 is connected (directly or indirectly) to the bottom surface 502b of the waveguide with a conductive strip 532.

[0028] As illustrated in Fig. 5, the dielectric substrate 507 containing the first array of micro-electromechanical devices 506 and the fourth array of micro-electromechanical devices 512 is normal to the waveguide path 504 at point 518. Other sets of arrays 508/514 on a dielectric substrate 509, and arrays 510/516 on a dielectric substrate 511 are normal to the waveguide path 504 at points 520 and 522, respectively. Between each of the arrays in a set of arrays there is an opening (e.g., 534, 536, 538) normal to the waveguide path 504 between the arrays (e.g., 506/512, 508/514, 510/516). The width of the opening between arrays of a set can be the same for all sets of arrays or can be different sizes.

[0029] Fig. 6 is a perspective view of a first row exemplary micro-electromechanical

device 600x and a second row exemplary micro-electromechanical device 600y on a dielectric substrate 609 from the exemplary embodiment shown in Fig. 5. The micro-electromechanical devices 600x and 600y respectively include a shutter 624x and 624y mounted on the substrate 609. The shutter 624x is connected to the top or bottom surface of a waveguide (depending if it is in a top or bottom array) by the conductive film 630. The shutters 624x and 624y are respectively mounted above irises 631x and 631y in the substrate 609. Sill electrodes 632x and 632y are respectively mounted below the irises 631x and 631y in the substrate 609. A voltage applied between the sill electrode 632 and the shutter 624 of a respective device by wires provides an electrostatic force between the shutter and the sill electrode. The electrostatic force pulls the shutter 624 down over the iris 631 toward the sill electrode 632 of the respective device.

[0030] The representation of the shutter 624x in Fig. 6 is an illustration of actuated state of the micro-electromechanical device 600x (e.g., a voltage is applied between the shutter 624x and the sill electrode 632x). The amount of voltage applied determines the amount of unrolling or actuation that the shutter 624x will undergo and the final position that the shutter will hold. The shutter 624x can unroll to and hold a position within a range of positions 633 depending upon the voltage applied between the shutter element 624x and the sill electrode 632x.

[0031] The second row exemplary electromechanical device 600y, as shown in Fig. 6, is not actuated until the shutter 624x of the first row exemplary micro-electromechanical device 600x overlaps or contacts the shutter 624y of the second row exemplary micro-

electromechanical device 600y. In general, a subsequent row of an array is not actuated until the row above has been fully actuated if the array is near the top surface or until the row below has been fully actuated if the array is near the bottom surface. A sill insulator can be used to prevent shorts between the sill and the shutter when a shutter is fully actuated. For example, as shown in Fig. 6, the shutter 624x of the first row exemplary micro-electromechanical device 600x is insulated from the sill electrode 632x by a sill insulator 634x when 624x of the first row exemplary micro-electromechanical device 600x overlaps or comes into contact with the shutter 624y of the second row exemplary micro-electromechanical device 600y. Subsequently, the shutter 624y can unroll to and hold a position within a range of positions 635 depending upon the voltage applied between the shutter element 624y of the second row exemplary micro-electromechanical device 600y and the sill electrode 632y.

[0032] The description of the micro-electromechanical devices 600x and 600y in Fig. 6 is for electro-mechanical devices in arrays adjacent to the top surface, such as 506-510 shown in Fig. 5. Micro-electromechanical devices for the arrays adjacent to the bottom surface, such as 512-516 shown in Fig. 5, can have the shutter mounted on the substrate below the iris in the substrate and the sill electrode mounted above the iris in the substrate. Each row of micro-mechanical devices within each array can have a sill electrode for all of the micro-mechanical devices in a row. Furthermore, the portion of a row x micro-electromechanical device having the coiled portion of shutter can protrude from a surface of the waveguide.

[0033] The embodiment in Fig. 5 can also be represented and modeled as shown in Fig. 3. For example, a first voltage applied to row x of the first array 506, the third array 510, the

fourth 512 and the sixth array that halfway closes the irises in row x of these respective arrays. The first voltage is also applied to row y of the second array 508 and the fifth array 514 so that the irises in row y of these respective arrays are halfway closed. A second voltage is applied to row x of the second array 508 and the fifth array 514 so that the irises in row y of these respective arrays are closed. The area of the actuated positions (i.e., area of closed or partially closed iris) for the shutters in the first array 506 can be summed together along with the susceptance of the substrate (which includes any unactuated devices) that the first array 506 is on and thus be collectively seen as the first shutter structure 424 in Fig. 4. Likewise, second array 508 can be seen as the second shutter structure 426, third array 510 can be seen as the third shutter structure 428, fourth array 512 can be seen as the fourth shutter structure 430, fifth array 514 can be seen as the fifth shutter structure 432, and sixth array 516 can be seen as the sixth shutter structure 434.

[0034] To achieve a result comparable to that of the Fig. 4 embodiment, the cross-sectional area of the waveguide path 404 at a point B in the opening Ob between the first shutter structure 424 and fourth shutter structure 430 of Fig. 4 can be substantially equal (i.e., to within ten percent, or more or less) to a summation of the open irises in the first array 506, the fourth array 512, and the opening 536 between the first and fourth arrays. The cross-sectional area of the waveguide path 404 at point C in the opening Oc between the second shutter structure 426 and the fifth shutter structure 432 the cross-sectional area of Fig. 4 is less because of the actuation of the shutters in both rows of the second array 508 and fifth array 514. The opening Oc between the second shutter structure 426 and fifth

shutter structure 432 can be substantially equal to a summation of the open irises in the second array 508, the fifth array 514, and the opening 536 between the first and fourth arrays. The cross-sectional area of the waveguide path 404 at point D in the opening Od between the third shutter structure 428 and sixth shutter structure 436 can be substantially equal to a summation of the open irises in the third array 510, the sixth array 516, and the opening 536 between the first and fourth arrays. Alternately, those skilled in the art will appreciate that each set of arrays can have a unique opening size to tune the sets of arrays for impedance matching purposes. Furthermore, some or all of the arrays can have more or less than two rows of micro-electromechanical devices.

[0035] The exemplary embodiments utilize irises or shutters arranged to change physical dimensions of the waveguide path. The irises or shutters, when extending from either the top or bottom of the waveguide, introduce capacitive susceptances. In addition, the irises or shutters when extending from either side of the waveguide, introduce inductive susceptances. Combinations of arrangements can be configured to introduce both inductive and capacitive susceptances.

[0036] Fig. 7 illustrates an exemplary radar system 700 having a plurality of dynamic inline phase shifters 701-705 connected to a radar transceiver 707. An actuator control circuit 709 is connected to the dynamic inline phase shifters 701-705 by wiring 711. The actuator control circuit controls the actuation of the electromechanical means in each of the dynamic inline phase shifters 701-705 and the phase shift of a signal traveling through a dynamic inline phase shifter. Each in line phase shifter can phase shift one of a transmitted 713 and received 715 radar signals. In addition, other types of signals, such as radio

signals, can be phase shifted.

[0037] Fig. 8 illustrates an exemplary embodiment of method 800 for dynamically phase shifting a signal. As shown in Fig. 8, an actuation signal is sent to the electro-mechanical device positioned adjacent to a waveguide containing the waveguide path 801. The physical dimensions of the waveguide path are changed by the actuation of the electro-mechanical device 803. Then a signal is inputted along the waveguide path so that a phase shifted signal is outputted 805.

[0038] It will be apparent to those skilled in the art that various changes and modifications can be made in the inline phase shifter of the present invention without departing from the spirit and scope thereof. Thus, it is intended that the present invention cover the modifications of this invention provided they come within the scope of the appended claims and their equivalents.